ACQUISITION OF STUDY REPORTS FOR LITERATURE REVIEW OF HORIZONTAL WELLS AND MODELS FOR HORIZONTAL WELL INJECTORS AND PRODUCERS.

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PART 1

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NUMERICAL MODELS OF HORIZONTAL PRODUCTION AND STEAM INJECTION WELLS

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S U M M A R Y

Two wellbore models were developed taking account of the main features of multiphase flow. The models can be incorporated into a steam injection simulator, after alterations are made to suit the requirements of a given simulator.

The steam injection well model simulates steam-water flow down a vertical section, surrounded by heat-conducting formations, which bends into a horizontal section, of arbitrary elevations, perforated in any desired manner. Several types of well completions (with regard to wellbore heat loss reduction) are allowed, and account is taken of the flow regimes in the wellbore. Given the steam-water mass flow rates at the perforations, the model calculates steam pressure, temperature, quality and heat loss. The horizontal section pressure distributions can be coupled to block pressures in a steam injection simulator through an iterative process, if desired. The model developed should give a better representation of flow into a horizontal well than is possible using the conventional approach of radial flow indices.

The production well model simulates three-phase isothermal flow into a horizontal well. The horizontal section is perforated in any desired manner, at which oil, water and gas flow rates are given. (The horizontal section may have variable inclinations with distance). The model then calculates the well pressure distribution, taking into account all aspects of multiphase flow. The pressure distribution can be used to recalculate the oil, water and gas rates. The model can be incorporated into a steam injection simulator.

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INTRODUCTION

Numerical simulation of horizontal wells in reservoir simulators is still rather approximate. The procedure often consists in assigning productivity indices to a suite of blocks, which may be connected in any configuration. The resulting representation of a horizontal (or inclined) well is tantamount to placing a typical vertical well in some other configuration. One shortcoming of this approach is that the pressure drop - and the multiphase flow leading to it - in the well is not accounted for. In some cases, the suite of blocks may be given a very high permeability to minimize the pressure contrast among the grid blocks, which are made as small in cross-sectional area as possible. This leads to computational problems, besides giving an incorrect representation of a horizontal well. (In the following, "horizontal well" will signify a well of any configuration, with sections inclined at given angles).

Horizontal wells can have important applications in steam injection, both as injectors and producers. An inadequate representation of a horizontal well could give an incorrect oil recovery or other performance index. Previous experience with horizontal wells in steam injection simulations tends to show that the answer is probably optimistic. Apart from the pressure drop limitation noted above, the inflow resistance of a grid block-type horizontal well would be lower than that in the case of a circular well, embedded in a rectangular grid block.

This project addresses some aspects of the numerical representation of horizontal steam injection and fluid

production wells. It is believed that this type of representation could be incorporated into an existing steam injection simulator. Some observations on such an application are offered in the last part of the Discussion.

OBJECTIVES

The objectives of this work were to develop numerical models of horizontal (meaning inclined in an arbitrary manner) steam injection and fluid production wells, which could be incorporated into a steam injection simulator. Specifically, the numerical models were to have the following features:

Steam Injection Well:

An injection well was to have a vertical section, surrounded by heat-conducting media, and bent into a horizontal section of given characteristics. The horizontal section was to have perforations at known locations. Steam-water flow throughout the well was to be simulated, accounting for flow regimes and pressure drop, and allowance was to be made for steam-water offtakes at different points along the length of the well. The offtake rates were to be specified at the various points.

Production Well:

A horizontal well, with specified inflow rates of oil, water and gas along the length of the well. Three-phase oil-water-gas flow in the well was to be simulated, accounting for flow regime, holdup, hydrostatic head and friction.

Note:It is to be noted that the objectives of the original proposal (please see Appendix A) were slightly different in the case of the production well. Originally it was intended to include the surrounding porous medium along with the horizontal wellbore, via a circular grid. However, following discussions with the PCEJ Technical Sub-Committee, it was decided to dispense with the grid, because such a well will have to be connected with the simulator grid in any case.

STEAM INJECTION WELL

Formulation

The steam injection well model developed for this study was designed to predict steam pressure (temperature), quality and heat loss as functions of depth and time, for a given steam injection rate schedule. The well is assumed to consist of a vertical section and a horizontal section. Figure 1 shows a schematic of the wellbore as simulated.

The vertical section is surrounded by heat conducting formations, leading to heat loss. The wellbore, over this section, may have any one of the desired completions, viz. steam in the annulus, gas in the annulus, insulated tubing, insulating liquid in the annulus, or combinations thereof.
The horizontal section can be equipped with perforations along the length of the well, for each of which an offtake mass rate of the steam-water mixture is specified. A pressure drop is allowed due to the change in the flow direction from vertical to horizontal. The changing flow regime in the wellbore is accounted for, and appropriate friction factors are calculated. The model output consists of pressure, temperature, and steam quality (also heat loss in the vertical section) as functions of distance and time. These variables can be used in a steamsimulator. Other information available from the simulation consists of the flow regime in the wellbore and temperature distribution in the formation surrounding the vertical section. The system modeled consists of three parts: (i) the fluid flow conduit, (ii) casing-tubing annulus, casing wall and cement, and (iii) the formation surrounding the wellbore. Within the conduit, steady, homogeneous two-phase flow of water and steam is assumed. This is described by

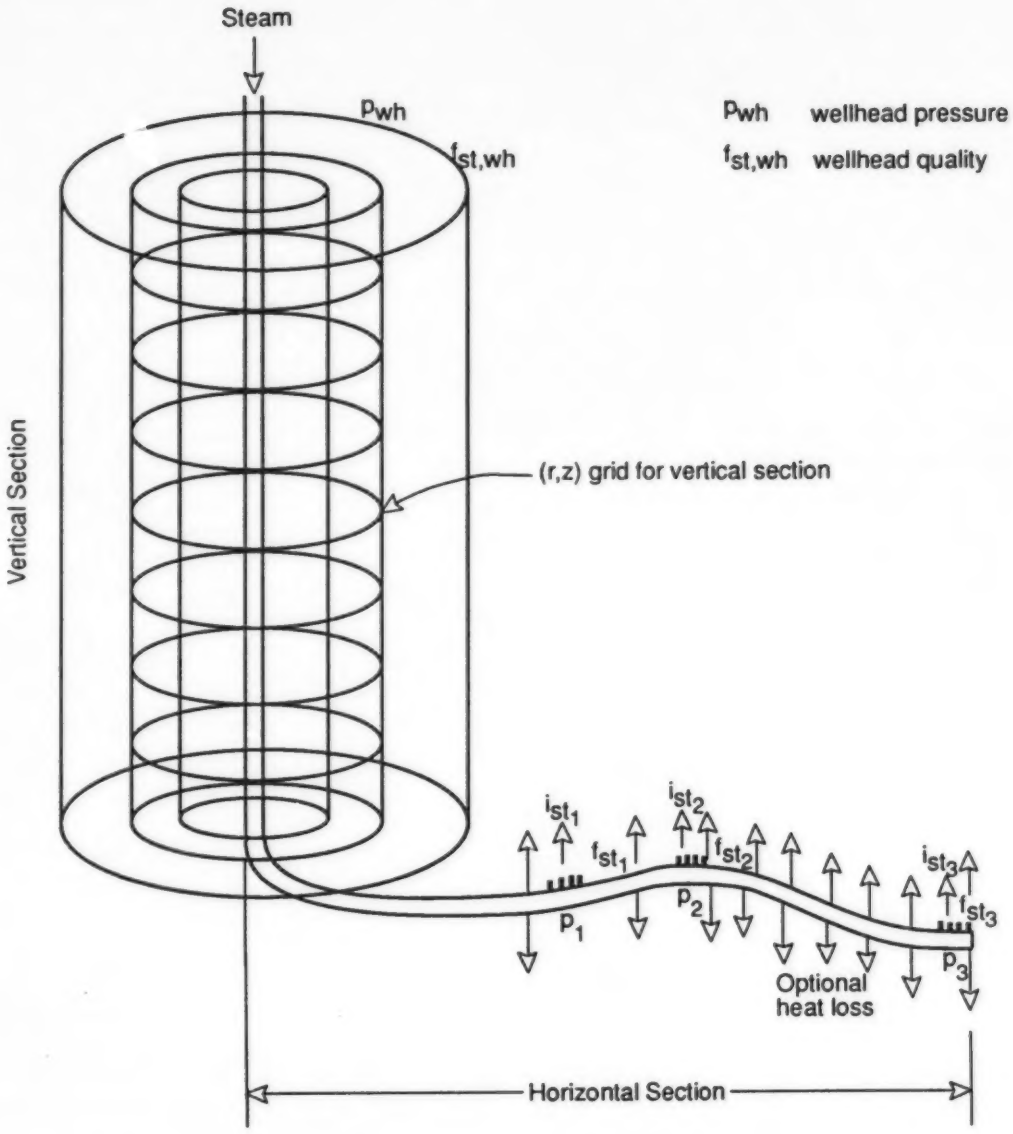

Figure 1 - Schematic of the representation of the steam injection well.

combining a two-phase mass balance with a momentum balance. The pressure gradient is calculated, using the acceleration gradient, in the manner of Orkiszewski (1967). The principal equations are given in Appendix B.

An energy balance is written for the two-phase flow under consideration. This contains a heat loss term, which is the heat loss to the formations surrounding the casing and cement. This is derived from the solution of the heat conduction equation in r,z coordinates. The equation is expressed by implicit finite differences and solved by a direct solution method (Crout's method). (Please note that the Ei function approach employed by previous investigators was not used, being less accurate; moreover, the present approach permits variable property vertical layers surrounding the wellbore). The resulting temperature distribution is used to calculate the heat loss term. This term requires the overall heat transfer coefficient, which represents the net resistance to heat flow, offered by the flowing fluid, tubing, insulation, annulus fluid, casing wall, and the cement sheath. Since the overall heat transfer coefficient involves the radiation and convection film coefficients, which are functions of the unknown temperature and steam quality, iteration is necessary.

Two-Phase Flow in the Wellbore

The existing literature on two-phase flow shows that the prevailing flow regime should be considered in determining the hold-up (hence the average mixture density) and the friction factor. Pipe roughness was allowed for. The following flow regimes were considered, using the correlations given by the authors indicated:

Flow Region	Correlation
Bubble/Plug Flow	Gould et al. (1974)
Slug/Froth Flow	Chierici et al. (1974)
Transition Flow	Duns and Ros (1961)

Results

A listing of the injection well model is given in Appendix C. The model developed was extensively tested for various steam injection conditions. Figure 2 shows wellbore pressure and steam quality distribution with distance for several offtake points as indicated, for a steam injection rate of 600 B/D, cold water equivalent (CWE). Figure 3 shows a similar plot for a steam injection rate three times as large. The greater pressure drop and the smaller drop in quality are evident at the higher rate. The frictional pressure drop results in some heat generation, which is responsible for an increase in steam quality.

It should be noted that a coarse grid was used to represent the vertical and horizontal sections. The program is rather time-consuming in view of the iterative solution used, and also because of the solution of the two-dimensional heat equation. Computer times depend strongly on how many nodes are used to represent the vertical section.

How the Model Can be Used in a Steam Simulator

The simulator described above can be incorporated into a steam injection simulator by coupling the horizontal wellbore nodes with the simulator blocks (horizontal or inclined configuration). At a given time in the simulation, the horizontal section pressure distribution is assumed. This is then used in conjunction with the latest block pressures to calculate the steam-water efflux rates at the specified perforations, using suitable skin factors to reflect the perforation type and density. These rates are then used in the wellbore simulator to determine the new pressure distribution. The process is repeated until agreement is obtained between two consecutive pressure distributions within a given tolerance. The offtake rates at this point are used to advance the

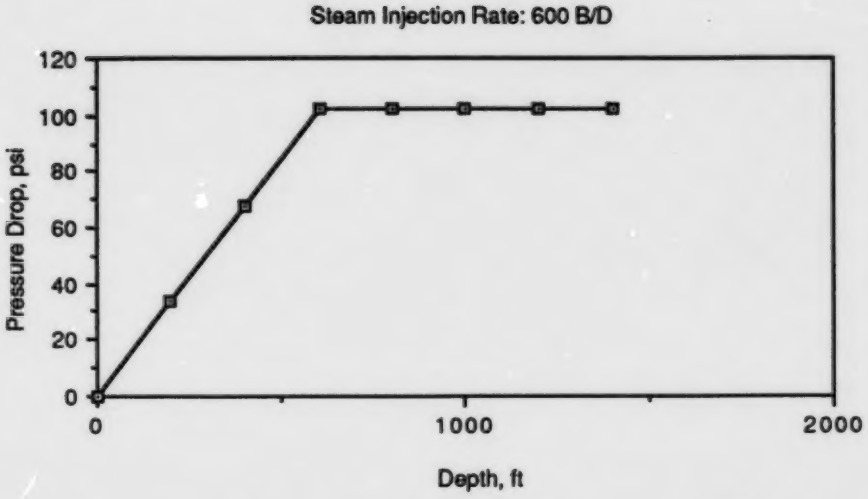

Fig. 2 - Pressure drop at a steam injection rate of 600 B/D.

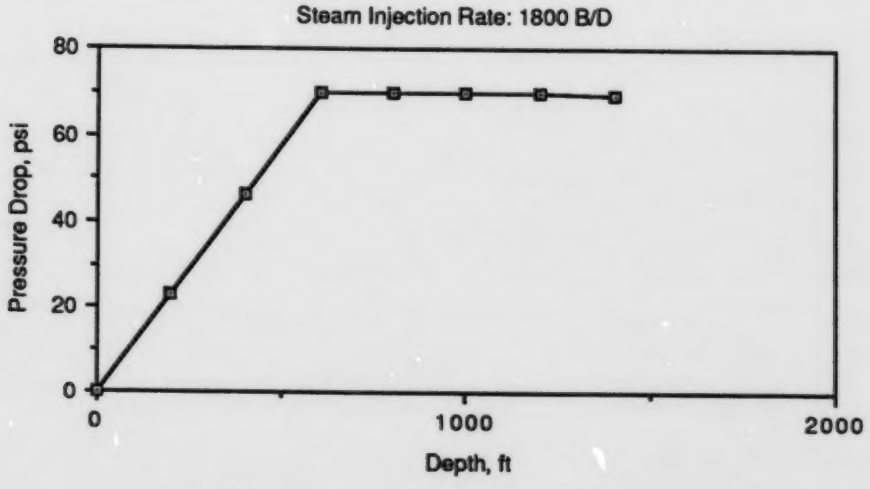

Fig. 3 - Pressure drop at a steam injection rate of 1800 B/D.

simulator solution by one time step. For the next time step, the overall procedure is repeated. In view of the large overhead that the wellbore model would add to the overall steam simulation, it may be desirable to do the wellbore computations every so-many time steps, rather than at each time step.

THREE-PHASE FLUID PRODUCTION WELL

Formulation

The three-phase horizontal wellbore model developed accouts for the flow of oil, water, and gas in a well, with sections inclined at various angles, and allowing three-phase intake at various points along the length of the well. The temperature is assumed to be constant along the length of the well at any given time. Flow regime (Fig. 4) is taken into account using the mathod of Beggs and Brill, with Palmer's modification (1973, 1982).

The theory of multiphase flow is highly empirical, unlike single phase flow, which can be treated by Navier-Stokes equations. It cannot be called even semi-empirical, because the only ananlytical part of multiphase flow in pipes is that the total pressure drop is the sum of hydrostatic head, friction drop, and the acceleration head.

When two (or more) fluids flow together, there is a difference in velocities in the general case. The resulting "slip" leads to changing flow regimes illustrated in Fig. 4. In the case of a horizontal well, the changing volumes of the three phases may cause different flow regimes in different sections of the pipe. Certain correlations (e.g. that of Lockhart and Martinelli (1949)) do not consider slip. Others, such as those of Dukler (1964) and Hagedorn and Brown (1965) do consider slip, but do not account for flow regime. The correlations of Beggs and Brill (1973, 1978) and Duns and Ros (1961) are more rigorous. In view of its overall success, the Beggs and Brill method was chosen for the production wellbore model.

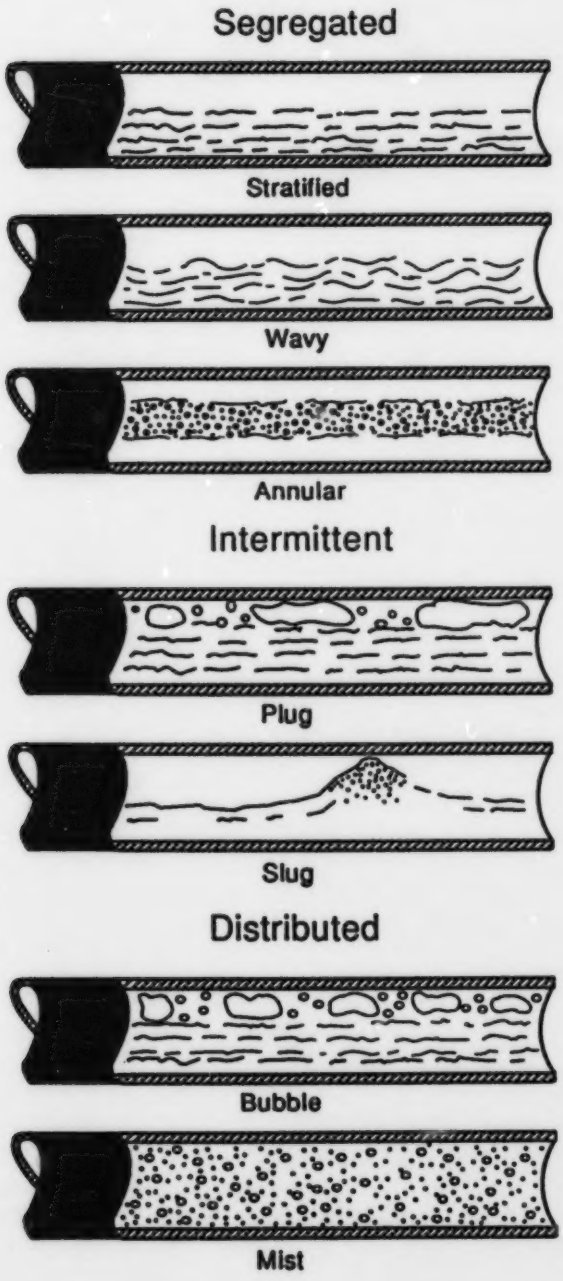

Fig. 4 - Flow regimes in multiphase flow in pipes.

Computational Procedure

The computational procedure for a given wellbore section consists of initialization and calculation of all relevant fluid properties, including the interfacial tensions, assuming a presure drop. After calculating all of the superficial velocities, the no-slip liquid hold-up is calculated. This is used for calculating four dimensionless flow numbers, which together with Froude's numbers are used to identify the flow regime, i.e. single phase liquid or gas, or multiphase distributed, intermittent, segregated or transition flow. Depending on the flow regime determined, the horizontal liquid hold-up is calculated. Next, the liquid hold-up coefficient and Palmer correction are determined, depending on the angle of inclination of the wellbore. At this point, the multiphase friction factor is calculated, employing a number of intermediate quantities. This is used to calculate the friction pressure gradient, elevation pressure gradient, and the acceleration pressure gradient. The total pressure gradient is used to calculate the new value of the pressure drop. If it agrees with the assumed value within the given tolerance, calculations are started for the next section of the wellbore. Otherwise, the entire procedure is repeated, using the new value of pressure drop. Appendix D gives a listing of the equations used and definition of symbols. Appendix E gives a listing of the computer program.

How the Model Can be Used in a Steam Simulator

The multiphase production wellbore model can be incorporated into a steam injection simulator, by coupling it with appropriate grid blocks. At a particular time in the simulation, the assumed (extrapolated) horizontal wellbore pressures are used together with the block pressures to determine the oil, water and gas inflow rates at the perforations, using predesignated skin factors. These rates are then used in the wellbore model to determine the new

pressure distribution. If it agrees with the assumed distribution within a preset tolerance, the main simulation is continued to the next time level. If not, the calculated pressure distribution is used to repeat the entire computation.

LIMITATIONS OF THE WELLBORE MODELS DEVELOPED

The steam injection and production well models developed in this study have a number of limitations, which are noted below:

1. In the case of the injection well, the formations surrounding the vertical section are assumed to be uniform in properties.
2. The grids used for both types of wells have equal increments.
3. In the case of the production well, a constant temperature is assumed at any given time.
4. The horizontal section of the steam injection well is assumed to be strictly horizontal.
5. Both wells utilize a pressure condition, in other words, at any given time in the main simulation, the inflow or outflow rates are governed by a pressure difference. This is considered to be more realistic than the specification of constant rates at each set of perforations.
6. The programs developed employ British units.

It is relatively simple to remove restrictions 1,2,4, and 6.

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APPENDIX A

Original Objectives of the Study

SCHEDULE A

attached to and made a part of an Agreement made between Petro-Canada Inc. and S.M. Farouq Ali and, dates as of 15 day of Jan, 1988

SCOPE OF SERVICES

Consultant shall provide the personnel and undertake the work which includes but is not limited to the supply of the following services:

The Consultant Shall,

a) Develop a wellbore model for a horizontal steam injector, incorporating effects of pressure drop, steam quality, perforation locations, flow regime, and other factors. The treatment will also provide the amount of formation heating for a number of situations to be determined in consultation with Petro-Canada.

b) Develop a model of a horizontal producer incorporating the effects of pressure drop in flow within the wellbore, perforation density, partial sanding, and two-phase flow. The production characteristics of such a well will be examined for a number of situations to be determined in consultation with Petro-Canada.

Both of the models, a) and b) should be in a form which can then be incorporated in ~~the 'Therm' or 'ISCOM' models of Scientific Software Intercomp or the Computer Modelling Group respectively~~. 2 thermal Simulator. The possibility of incorporating them into the "Therm" or "ISCOM" models may be examined.

APPENDIX B

Key Equations Used for the Steam Injection Well

The wellbore model developed for this study was designed to predict steam pressure (temperature), quality, and heat loss as functions of depth and time. The sand face steam pressure and quality were then input as functions of time into the steamflood simulator.

The system to be modeled consists of three parts: (i) the fluid flow conduit, tubing or casing-tubing annulus, (ii) casing-tubing annulus, casing wall, and the cement sheath, and (iii) the formation surrounding the wellbore. Within the conduit, steady, homogeneous two-phase flow of water and steam is assumed. This is described by combining a two-phase mass balance with a momentum balance, and is as follows (the vertical coordinate z is taken positive in the downward direction):

$$144\frac{dp}{dz}-\overline{\rho}_m\frac{g}{g_c}+\overline{\rho}_m\frac{dW_f}{dz}+\frac{\overline{\rho}_m v_m}{g_c}\frac{dv_m}{dz}=0$$

The subscript m in the above equations refers to the steam-water mixture.

The pressure gradient is given by

$$\frac{dp}{dz}=\frac{1}{144}\left(\frac{\overline{\rho}_m\frac{g}{g_c}-\tau_f}{1-\gamma_a}\right),$$

where g_a is the accleration gradient defined in the manner of Orkiszewski (1967):

$$\gamma_a=\frac{wq_s}{144A^2g_c\overline{p}}.$$

Next, an energy balance is written for the flow under consideration, which is as follows:

$$\frac{\dot{Q}}{3600}+w\frac{d}{dz}\left(h_m+\frac{v_m^2}{2g_cJ_c}-\frac{g}{g_cJ_c}z\right)=0,$$

where the enthalpy h_m of a two-phase steam-water mixture is given by

$$h_m = h_m(f_{st}, p) = (1 - f_{st})h_w + f_{st}h_s,$$

where f_{st} is steam quality, and h_w and h_s are enthalpies of saturated water and steam, respectively. These were calculated from the equations given in the previous section. Using these equations, and allowing for heat loss from the tubing to the cement sheath, given by

$$\dot{Q} = 2\pi r_{te} U_{te} (T - T_{cem}),$$

the energy balance equation takes the form

$$C_1 \frac{df_{st}}{dz} + C_2 f_{st} + C_3 = 0$$

Here U_{te} represents the net resistance to heat flow offered by the flowing fluid, tubing insulation, annulus fluid, casing wall, and the cement sheath, and is given by

$$U_{te} = \frac{1}{r_{te}} \left[\frac{\ln \frac{r_{ins}}{r_{te}}}{k_{hins}} + \frac{1}{r_{ins}(h_r + h_c)} + \frac{\ln \frac{r_{cem}}{r_{ce}}}{k_{hcem}} \right]^{-1}.$$

In the above equations the subscript "cem" refers to the cement sheath, "ins" refers to tubing insulation, if any, "ce" refers to casing exterior, and "te" refers to tubing exterior. The coefficients h_r and h_c are radiation and convection heat transfer coefficients, calculated in the conventional manner.

The heat loss term $\dot{Q}$ was calculated by solving the two-dimensional radial heat conduction equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_f}{\partial r}\right) + \frac{\partial^2 T_f}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T_f}{\partial t},$$

where T_f is the temperature of surrounding formations and a is thermal diffusivity. This is a new feature; the previous authors have used the approximation of the Ei-function to estimate the temperatures around the wellbore, and thus derive the heat loss rate.

The boundary and initial conditions for the solution of the above equations are:

Initial Condition

$$T_f = T_a + \gamma z \text{ at } t = 0$$

Boundary Conditions

$$T_f = T_a \text{ at } z = 0$$

$$T_f = T_R \text{ at } z = Z$$

$$\dot{Q} = -2\pi r k_{hf} \frac{\partial T_f}{\partial r} \text{ at } r = r_{com}$$

$$\frac{\partial T_f}{\partial r} = 0 \text{ at } r = \infty$$

APPENDIX C

Listing of the Injection Well Program

```
      C   HORINJ91 * CALCULATION OF DOWNHOLE STEAM PRESSURE AND QUALITY IN A
      C                VERTICAL/HORIZONTAL WELL * S.M. FAROUQ ALI * DEC 1988
      C
      C DATA INPUT:
      C CARD 1 (2I5): NSWT (=0 MEANS NO ITERATIONS DETAILS, 1 DETAILS), NO OF RUNS
      C CARD 2 TO N (FREE FORM): BLOCK NO., LB/HR OF STEAM TAKEN OFF AT THE BLOCK
      C ***** NOTE: THE LAST CARD ABOVE MUST HAVE 0   0 ON IT *****
      C CARD N+1 (6F10.7): TBG  IN RAD, FT; TBG OUT RAD, FT; CSG IN RAD, FT; CSG OUT
      C                    RAD, FT; CEMENT RAD, FT; ROUGHNESS< FT
      C CARD N+2 (3I5): 1 IF INSULATED, 0 IF NOT; 0 IF LIQ IN ANNULUS, 1 IF GAS, 2
      C                 IF GEL, 3 IF INJ IN ANNULUS; 1 FOR PROD, -1 FOR INJ WELL
      C CARD N+3 (3F10.5): THERM COND OF ANNULUS FLUID; TC  OF CEMENT; TC OF
      C                    SURROUNDING FORMATIONS, ALL IN BTU/HR-FT-F
      C CARD N+4 (4F10.5): ANNULUS FLUID DENSITY, LB/CUFT; VISCOSITY, CP; SP HEAT,
      C                    BTU/LB-F; THERMAL EXP COEFF, PER F
      C CARD N+5 (5F10.5): EMISSIVITY IN CSG; OUT TBG; THERMAL DIFFUSIVITY, FT2/HR;
      C                    GEOTHERMAL GRAD, F/FT; CIRCULAR GRID GEOMETRIC RATIO
      C CARD N+6 (6F10.5): DEPTH, FT; SURF TEMP, F; FORM TEMP, F; WELLHEAD QUALITY,
      C                    FRAC; WELLHEAD INJ RATE, LB/HR; WELLHEAD PRESS, PSIA
      C CARD N+7 (2I5,F10.5,2I5): NO. OF RADIAL BLOCKS; NO. OF AXIAL BLOCKS; TIME
      C                           STEP, DAY; NO.TIME STEPS;NO. VERT BLKS
      C CARD N+8 (4F10.5): INITIAL U-VALUE; PRESS TOLERANCE, PSI; Q TOL; U TOL
      C CARD N+9 (3F10.5): INSUL THICK, FT; TC OF INSUL, BTU/HR-FT-F; INSUL EMISS
      C
      C
            IMPLICIT REAL*8(A-H,O-Z)
            INTEGER REGION
            REAL*8 JC,MRT,MRT1(100)
            COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
           1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
           2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
            DIMENSION HRTP(11),DELDPH(11),ISKIP(100)
            COMMON /PRE/ QXAV,TOLP,XMULT(100),ITERP,REGION
            COMMON /NEWTO/ ITERF
            COMMON /HEA/ TEMCI(11),      ETO,EINS,ECI,DENAN,HCNAN,HCNINS,
           1HCNCEM,HECAN,HSPAN,      RADINS,RADCI,RADCO,TOLU,   VISAN,INDAN,
           2INDINS,ITERU
            COMMON /CONDU/ A1,DELTIM,DFNF,HCNF,RR,TEMA,TEMR,TIM,NTIM,NTIMI
            COMMON /ENERG/ QX(11),MRT1,NZZ
            READ(5,106)NSWT,NRUNS
            DO 99999 NRUN=1,NRUNS
            PRINT 99998,NRUN
      99998 FORMAT('1',80('*')/' ',40('*'),' RUN',I3,1X,40('*')/' ',80('*'
           1))
            DO 5082 K=1,100
      5082  MRT1(K)=0.D0
            DO 5083 K=1,11
      5083  HRT(K)=0.D0
            NOFF=0
            DO 508 K=1,100
            READ*,I,XXX
            NOFF=NOFF+1
            IF(I.EQ.0)GO TO 5080
            MRT1(I)=XXX
      508   CONTINUE
      5080  CONTINUE
            NOFF=NOFF-1
            READ(5,107) RADTI,RADTO,RADCI,RADCO,RADCEM,ROUGHI
```

```
      READ(5,100) INDINS,INDAN,INDFLO
      READ(5,102) HCNAN,HCNCEM,HCNF
      READ(5,104) DENAN,VISAN,HSPAN,HECAN
      READ(5,101) ECI,ETO,DFNF,A1,RR
      READ(5,108) DPH,TEMA,TEMR,QXI,MRT,PRSSUR
5081  READ(5,106) NR,NZ,DELTIM,NTIMI,NZZ
      READ(5,104) UINI,TOLP,TOLQ,TOLU
      READ(5,102) THICK ,HCNINS,EINS
      RADINS=RADTO+THICK
  103 GRV=32.17
      GRVC=32.17
      JC=778.0
      DIA=RADTI*2.0
      DIATO=RADTO*24.0
      DIACO=RADCO*24.0
      DIACEM=RADCEM*24.0
      ARA=(RADTI**2)*3.1416
      DELZ=DPH/(NZ-1)
      NTAP=IDINT((DEPTH1+1.)/DELZ)
      TIMI=DELTIM*NTIMI
      DO 501 II=1,NZ
501   XMULT(II)=1.DO
      NZZP=NZZ+1
      DO 502 II=NZZP,NZ
502   XMULT(II)=0.DO
      IF(INDFLO.EQ.2) TEMX=TEMA
      IF(INDFLO.EQ.2) TEMA=TEMR
      IF(INDFLO.EQ.2) TEMR=TEMX
      WRITE (6,950)
      VERTS=DELZ*NZZ
      HORIZS=DELZ*(NZ-NZZ-1)
      PRINT*,'LENGTH OF VERTICAL SECTION ',VERTS,' FT'
      PRINT*,'LENGTH OF HORIZONTAL SECTION ',HORIZS,' FT'
      WRITE(6,967)
      PRINT 95000,(MRT1(I),I,I=1,NZ)
95000 FORMAT(' ','LB/HR OF STEAM= ',E9.4,' OFFTAKE AT NODE ',I3/)
      WRITE(6,967)
      IF(INDFLO.EQ.1) WRITE(6,901)
      IF(INDFLO.EQ.-1) WRITE(6,902)
      IF(INDINS.EQ.1) WRITE(6,903)
      IF(INDINS.EQ.0) WRITE(6,904)
      IF(INDAN.EQ.0) WRITE(6,905)
      IF(INDAN.EQ.1) WRITE(6,906)
      IF(INDAN.EQ.2) WRITE(6,920)
      IF(INDAN.EQ.3) WRITE(6,921)
      WRITE(6,908) DPH
      IF(INDFLO.EQ.2) GO TO 110
      WRITE(6,909) PRSSUR,QXI,MRT
      GO TO 111
  110 WRITE(6,922) PRSSUR,QXI,MRT
  111 IF(INDFLO.EQ.2) GO TO 112
      WRITE(6,910) TEMA,TEMR,A1
      GO TO 113
  112 WRITE(6,910) TEMR,TEMA,A1
      WRITE(6,907) DIATO,DIACO,DIACEM
      WRITE(6,919) ROUGHI
  113 WRITE(6,911) NR,NZ
      WRITE(6,912) RR,DELZ
```

```
      WRITE(6,913) TIMI,DELTIM
      WRITE(6,914) HCNAN,HCNCEM,HCNF
      WRITE(6,915) ETO,ECI,DFNF
      WRITE(6,916) DENAN,VISAN,HSPAN
      IF(INDINS.EQ.0) GO TO 105
      WRITE(6,917) THICK,HCNINS,EINS
  105 WRITE(6,918) TOLP,TOLQ,TOLU
      WRITE(6,960)
      WRITE(6,967)
      WRITE(6,967)
      PRS(1)=PRSSUR
      U(1)=UINI
      QX(1)=QXI
      MRT=MRT/3600.0
      MRTSAV=MRT
      DO 510 K=1,NZ
  510 MRT1(K)=MRT1(K)/3600.D0
      DO 900 M=2,NZ
      MRT=MRT-MRT1(M)
      MM1=M-1
      ITERQ=1
      IF(INDFLO.EQ.2) GO TO 201
      QXXT=QX(MM1)-0.00006*DELZ
      GO TO 200
  201 QXXT=QX(MM1)+0.00006*DELZ
  200 CONTINUE
      IF(QXXT.GT.1.0) QXXT=1.0
      IF(QXXT.LT.0.0) QXXT=0.0
      QXAV=(QX(MM1)+QXXT)/2.0
      CALL PRES                                                    CALL
      CALL HEAT
      HRT(1)=HRT(2)
      CALL ENERGY
      MAXM=M
      IF(QX(M).GE.0.0) GO TO 202
      IF(ITERQ.GE.3) GO TO 203
  202 DELQX=QX(M)-QXXT
      IF(DABS(DELQX).LE.TOLQ) GO TO 900
      IF(ITERQ.GE.21) GO TO 900
      ITERQ=ITERQ+1
      QXXT=QX(M)
      GO TO 200
  203 QX(M)=0.0
      WRITE(6,961) M,ITERQ,ITERU,ITERP,ITERF,REGION
      GO TO 940
  900 WRITE(6,961) M,ITERQ,ITERU,ITERP,ITERF,REGION
  940 RAD1=RADCEM
      RAD2=RADCEM*RR
      RAD3=RADCEM*(RR**2)
      RAD4=RADCEM*(RR**3)
      RAD5=RADCEM*(RR**4)
      RAD6=RADCEM*(RR**5)
      MRT=MRT*3600.0
      IF(INDFLO.EQ. 1) GO TO 204
      HRTT=0.0
      DO 205 M=2,MAXM
      IF(M.EQ.2) HRT(1)=HRT(1)*3600.0
      HRT(M)=HRT(M)*3600.0
```

```
405           HRTT=HRTT+DELZ/2.0*(HRT(M-1)+HRT(M))
406           HRTGA=MRTSAV*(QXI*1119.0*(PRSSUR**0.01267)+(1.0-QXI)*91.D0*
407          1(PRSSUR**0.2574D0))
408         205 HRTP(M)=(HRTT/(HRTGA*3600.D0))*100.0
409         204 CONTINUE
411           DO 206 M=1,NZ
412           IF(INDFLO.NE.2) DELDPH(M)=(M-1)*DELZ
413           IF(INDFLO.EQ.2) DELDPH(M)=DPH-(M-1)*DELZ
414         206 CONTINUE
418           WRITE(6,967)
419           WRITE(6,913)TIMI,DELTIM
420           WRITE(6,962)
421           IF(INDFLO.EQ. 1) GO TO 207
422           WRITE(6,963) (DELDPH(M),PRS(M),QX(M),TEM(M),TEMCI(M),U(M),DENAV(M)
423          1,HRT(M),HRTP(M),M=1,MAXM)
424           GO TO 208
425         207 WRITE(6,969) (DELDPH(M),PRS(M),QX(M),TEM(M),TEMCI(M),U(M),
426          1DENAV(M),M=1,MAXM)
427         208 WRITE(6,964)  TIM
428           WRITE(6,967)
429           WRITE(6,965)
430           WRITE(6,968) RAD1,RAD2,RAD3,RAD4,RAD5
431           WRITE(6,967)
432           WRITE(6,966) (DELDPH(M),(T(I,M),I=1,5),M=1,NZZ)
433       99999 CONTINUE
435         100 FORMAT(3I5)
436         101 FORMAT(5F10.5)
437         102 FORMAT(3F10.5)
438         104 FORMAT(4F10.6)
439         106 FORMAT(2I5,F10.5,2I5)
440         107 FORMAT(6F10.7)
441         108 FORMAT(6F10.4)
443         950 FORMAT(1H1,48X,12HINPUT   DATA)
444         901 FORMAT(1HO,46X,24HTYPE OF FLOW= PRODUCTION)
445         902 FORMAT(1HO,46X,23HTYPE OF FLOW= INJECTION)
446         903 FORMAT(1HO,46X,22HTUBING INSULATION= YES)
447         904 FORMAT(1HO,46X,21HTUBING INSULATION= NO)
448         905 FORMAT(1HO,46X,30HTYPE OF ANNULAS FLUID= LIQUID )
449         906 FORMAT(1HO,46X,26HTYPE OF ANNULAS FLUID= GAS)
450         920 FORMAT(1HO,46X,27HTYPE OF ANNULAS FLUID= GELL)
451         921 FORMAT(1HO,46X,22HCASE OF FLOW IN CASING)
452         907 FORMAT(1HO,6X,12HTUBING SIZE=,F6.3,5H INCH,17X,12HCASING SIZE=,F6.
453            13,5H INCH,17X,14HBOREHOLE SIZE=,F6.3,5H INCH)
454         908 FORMAT(1HO,46X,6HDEPTH=,F7.1,5H FEET)
455         909 FORMAT(1HO,6X,20HPRESSURE AT SURFACE=,F7.1,5H PSIA,8X,25HSTEAM QUA
456            1LITY AT SURFACE=,F6.3,9X,15HMASS FLOW RATE=,F8.1,6H LB/HR)
457         922 FORMAT(1HO,6X,22HPRESSURE AT RESERVOIR=,F7.1,5H PSIA,6X,27HSTEAM Q
458            1UALITY AT RESERVOIR=,F6.3,7X,15HMASS FLOW RATE=,F8.1,6H LB/HR)
459         910 FORMAT(1HO,6X,24HATMOSPHERIC TEMPERATURE=,F5.1,2H F,9X,22HRESERVOI
460            1R TEMPERATURE=,F5.1,2H F,11X,20HGEOTHERMAL GRADIENT=,F5.3,5H F/FT)
461         911 FORMAT(1HO,6X,27HGRID POINTS IN R-DIRECTION=,I2,11X,27HGRID POINTS
462            1 IN Z-DIRECTION=,I3)
463         912 FORMAT(1HO,6X,24HRATIO OF RADIUS OF GRID=,F4.1,12X,5HDELZ=,F6.1,5H
464            1 FEET)
465         913 FORMAT(1HO,6X,13HTIME ELAPSED=,F7.1,5H DAYS,15X,7HDELTIM=,F5.1,5H
466            1DAYS)
467         914 FORMAT(1HO,6X,32HTHERMAL CONDUCTIVITY OF ANNULAS=,F6.4,2X,31HTHERM
468            1AL CONDUCTIVITY OF CEMENT=,F6.4,3X,30HTHERMAL CONDUCTIVITY OF EART
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     2H=,F6.4)
915 FORMAT(1HO,6X,21HEMISSIVITY OF TUBING=,F6.4,13X,21HEMISSIVITY OF C
    1ASING=,F6.4,13X,29HTHERMAL DIFFUSIVITY OF EARTH=,F6.4,9H SQFT/DAY)
916 FORMAT(1HO,6X,25HDENSITY OF ANNULAR FLUID=,F6.4,6H LB/CF,3X,21HVIS
    1COSITY OF ANNULAR=,F6.4,10H LBM/FT-HR,3X,31HSPECIFIC HEAT OF ANNUL
    2AR FLUID=,F6.4,9H BTU/LB-F)
917 FORMAT(1HO,6X,24HTHICKNESS OF INSULATION=,F6.4,10X,28HTHERMAL COND
    1. OF INSULATION=,F6.4,6X,25HEMISSIVITY OF INSULATION=,F6.4)
918 FORMAT(1HO,6X,15HTOLERANCE OF P=,F5.2,5H PSIA,15X,15HTOLERANCE OF
    1Q=,F6.3,19X,15HTOLERANCE OF U=,F5.2)
919 FORMAT(1HO,46X,26HTUBING RELATIVE ROUGHNESS=,F7.5)
960 FORMAT(1H1,48X,13HOUTPUT   DATA)
961 FORMAT(1HO,6X,2HM=,I2,10X,6HITERQ=,I3,10X,6HITERU=,I3,10X,6HITERP=
    1,I3,10X,6HITERF=,I3,10X,7HREGION=,I2)
962 FORMAT(1H1,18X,8HPRESSURE,3X,13HSTEAM QUALITY,3X,10HFLUID TEMP,3X,
    111HCASING TEMP,3X,10HVALUE OF U,3X,12HAVG. DENSITY,3X,14HHEAT LOSS
    2 RATE,3X,11H% HEAT LOSS)
963 FORMAT(1HO,2HZ=,F7.1,3H FT,5X,F8.2,6X,F7.4,8X,F6.1,8X,F6.1,7X,F6.3
    1,7X,F6.2,10X,F7.1,9X,F6.2)
964 FORMAT(1H1,6X,22HROCK TEMPERATURE AFTER,F6.1,5H DAYS)
     WRITE(6,967)
965 FORMAT(1HO,26X,3HI=1,9X,3HI=2,9X,3HI=3,9X,3HI=4,9X,3HI=5)
966 FORMAT(1HO,6X,2HZ=,F7.1,3H FT,5F12.1)
967 FORMAT(1HO,80('*'))
968 FORMAT(1HO,10X,2HR=,9X,F8.3,3H FT,F10.3,3X,F10.3,2X,F10.3,3X,F10.3
    1)
969 FORMAT(1HO,2HZ=,F7.1,3H FT,5X,F8.2,6X,F7.4,8X,F6.1,8X,F6.1,7X,F6.3
    1,7X,F6.2)
     STOP
     END
     SUBROUTINE PRES                                                    PRES
     IMPLICIT REAL*8(A-H,O-Z)
     INTEGER REGION
     REAL*8 JC,MRT,MRT1(100)
     REAL*8 LIMIT1,LIMIT2,NUMQGV,NUMQLV,NUMQMV,NUMQW
     COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
    1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
    2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
     COMMON /PRE/ QXAV,TOLP,XMULT(100),ITERP,REGION
     COMMON /PRENEW/ REYQ,XNEW,ROUGH
     COMMON /ENERG/ QX(11),MRT1,NZZ
     ITERP=1
     IF(INDFLO.EQ.2) GO TO 305
     PRSXT=PRS(M-1)+0.433/6.0*DELZ*INDFLO
     GO TO 300
305  PRSXT=PRS(M-1)-0.433/6.0*DELZ
300  PRSAV=(PRS(M-1)+PRSXT)/2.0
     TEMAV=115.1*(PRSAV**0.225)
     ROUGH=ROUGHI
     SFT=0.128
     DENG=1.0/(363.9*(PRSAV**(-0.9588)))
     DENL=1.0/(0.0157+(8.6D-5)*(PRSAV**(0.225))+(2.0D-4)*(PRSAV**(0.450
    1)))
     DENAV(1)=1.0/(QXI/DENG+(1.0-QXI)/DENL)
     RTEL=MRT*(1.0-QXAV)/DENL
     RTEG=MRT*QXAV/DENG
     RTEM=RTEL+RTEG
     VISL=2.185/(0.04012*TEMAV+(5.154D-6)*(TEMAV**2)-1.0)
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      VISG=(1.0D-4)*(82.2516+0.17815*TEMAV+(6.59D-5)*(TEMAV**2)-DENG*(31
     1.45-0.05253*TEMAV))
      VELVG=RTEG/ARA
      VELVM=RTEM/ARA
  301 NUMQLV=RTEL/ARA*(DENL/GRV/SFT)**0.25
      IF(NUMQLV.LT.0.D0)NUMQLV=1.D-10
      NUMQGV=RTEG/ARA*(DENL/GRV/SFT)**0.25
      NUMQMV=1.071-0.2218*(VELVM**2)/DIA
      IF(NUMQMV.LE.0.13)  NUMQMV=0.13
      RATIOG=RTEG/RTEM
      LIMIT1=50.0+36.0*NUMQLV
      LIMIT2=75.0+84.0*(NUMQLV**0.75)
      IF(NUMQMV.GE.RATIOG) GO TO 302                                  BUBBLE
      IF(NUMQGV.LT.LIMIT1) GO TO 303                                  SLUG
      IF(NUMQGV.GT.LIMIT2) GO TO 304                                  MIST
      REGION=3                                                        TRANSITI
      GO TO 310
  303 REGION=2
      GO TO 310
  304 REGION=4
      GO TO 320
  302 REGION=1
      VELVS=1.53*(SFT*GRV*GRVC*(DENL-DENG)/(DENL**2))**0.25
      HOLDG=0.5*((1.0+VELVM/VELVS)-DSQRT((1.0+VELVM/VELVS)**2-4.0*VELVG/
     1VELVS))
      DENAV(M)=DENG*HOLDG+DENL*(1.0-HOLDG)
      VELVL=RTEL/ARA/(1.0-HOLDG)
      REYQ=1488.0*VELVL*DIA*DENL/VISL
      CALL NEWTON
      FFC=1.0/(XNEW**2)
      FRIC=FFC*DENL*VELVL**2/(8.0*GRVC*DIA)
      GO TO 392
  310 IF(REGION.EQ.3) RTEG=LIMIT1*ARA*(GRV*SFT/DENL)**0.25
      RTEM=RTEG+RTEL
      VELVM=RTEM/ARA
      VELVB=0.2*VELVM+0.35*DSQRT(GRV*DIA)
      REYQ=1488.0*VELVM*DIA*DENL/VISL
      HOLDG=RTEG/(RTEM+ARA*VELVB)
      IF(HOLDG.LT.1.E-20)HOLDG=0.D0
      DENAVS=DENG*HOLDG+DENL*(1.0-HOLDG)
      CALL NEWTON
      FFC=1.0/(XNEW**2)
      FRICS=(1.0-HOLDG)*FFC      *(VELVM**2)/(8.0*GRVC*DIA)*DENL
  312 IF(REGION.EQ.3) GO TO 320
      GO TO 390
  320 IF(REGION.EQ.3) RTEGM=LIMIT2*ARA*(GRV*SFT/DENL)**0.25
      IF(REGION.EQ.3) DENG=DENG*RTEG/RTEGM
      IF(REGION.EQ.3) VELVG=RTEGM/ARA
      IF(REGION.EQ.3) RTEG=RTEGM
      RTEM=RTEG+RTEL
      HOLDG=RTEG/RTEM
      DENAVM=HOLDG*DENG+(1.0-HOLDG)*DENL
      NUMQW=(4.52D-7)*(VELVG*VISL /SFT)**2*DENG/DENL
      IF(NUMQW.GT.0.005) GO TO 321
      ROUGH=34.0*SFT/(DENG*VELVG**2*DIA)
      GO TO 322
  321 ROUGH=174.8*SFT*(NUMQW**0.302)/(DENG*VELVG**2*DIA)
  322 IF(ROUGH.LE.0.05) GO TO 323
```

```
      FFC=1.0/(4.0*(DLOG10(0.27*ROUGH))**2)+0.268*ROUGH**1.73
      GO TO 324
323   REYQ=1488.0*VELVG*DIA*DENG/VISG
      CALL NEWTON
      FFC=1.0/(XNEW**2)
      IF(INDFLO.NE.-1) GO TO 325
324   FRICM=FFC*DENG*(VELVG**2)/(8.0*GRVC*DIA)
      GO TO 326
325   FRICM=FFC*DENG*(VELVG**2)/(2.0*GRVC*DIA)
326   IF(REGION.EQ.3) GO TO 330
      GO TO 391
330   DENAV(M)=DENAVS*(LIMIT2-NUMQGV)/(LIMIT2-LIMIT1)+DENAVM*(NUMQGV-LIM
     1IT1)/(LIMIT2-LIMIT1)
      RATIOG=RTEG/RTEM
      FRIC=    FRICS *(LIMIT2-NUMQGV)/(LIMIT2-LIMIT1)+FRICM *(NUMQGV-LIM
     1IT1)/(LIMIT2-LIMIT1)
      GO TO 392
390   DENAV(M)=DENAVS
      FRIC=FRICS
      GO TO 392
391   DENAV(M)=DENAVM
      FRIC=FRICM
392   IF(REGION.EQ.4) GO TO 393
      ACCEL=0.0
      GO TO 394
393   ACCEL=MRT*RTEG/(GRVC*(ARA**2)*PRSAV*144.0)
394   IF(INDFLO.EQ.2) GO TO 396
      PRINT*,FRIC,DENAV(M),'FRIC,DENAV'
      PRS(M)=PRS(M-1)+DELZ/144.0/(1.0-ACCEL*INDFLO)*
     1(XMULT(M)*DENAV(M)+FRIC*INDFLO)
      GO TO 397
396   PRS(M)=PRS(M-1)-DELZ/144./(1.0-ACCEL)*(XMULT(M)*DENAV(M)+FRIC)
397   DELPRS=PRS(M)-PRSXT
      IF(DABS(DELPRS).LE.TOLP) GO TO 395
      IF(ITERP.GE.21) GO TO 395
      ITERP=ITERP+1
      PRSXT=PRS(M)
      GO TO 300
395   RETURN
      END
      SUBROUTINE NEWTON                                              NEWTON
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 JC,MRT,MRT1(100)
      COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
     1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
     2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
      COMMON /NEWTO/ ITERF
      COMMON /PRENEW/ REYQ,XNEW,ROUGH
      ITERF=1
      X=5.0
400   EXARG=1.1513*X
      IF(DABS(EXARG).GT.100.)GO TO 402
      FUNC=2.51/REYQ*X-DEXP(-1.1513*X)+ROUGH/3.7
      DFUNC=2.51/REYQ+1.1513*DEXP(-1.1513*X)
      XNEW=X-FUNC/DFUNC
      DELX=XNEW-X
      ITERF=ITERF+1
      IF(DABS(DELX).LE.0.1   ) GO TO 401
```

```
      IF(ITERF.GE.51) GO TO 402
      X=XNEW
      GO TO 400
  401 RETURN
  402 X=5.
      RETURN
      END
      SUBROUTINE HEAT                                                    HEAT
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 JC,MRT,MRT1(100)
      COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
     1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
     2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
      COMMON /HEA/ TEMCI(11),      ETO,EINS,ECI,DENAN,HCNAN,HCNINS,
     1HCNCEM,HECAN,HSPAN,      RADINS,RADCI,RADCO,TOLU,   VISAN,INDAN,
     2INDINS,ITERU
      COMMON /ENERG/ QX(11),MRT1,NZZ
      ITERU=1
      TEM(1)=115.1*(PRS(1)**0.225)
      TEM(M)=115.1*(PRS(M)**0.225)
      IF(M.EQ.2) UI=UINI
      IF(M.GT.2) UI=U(M-1)
  500 CONTINUE
      NSAVE=NZ
      NZ=NZZ
      IF(M.GE.NZZ)GO TO 50401
      CALL CONDUC                                                        CALL
      NZ=NSAVE
      TEMCEM=T(1,M)
      IF(INDINS.EQ.0) GO TO 501
      TEMINS=TEM(M)-RADTO*DLOG(RADINS/RADTO)/HCNINS*UI*(TEM(M)-TEMCEM)
      GO TO 502
  501 IF(INDAN.EQ.3) GO TO 509
      TEMINS=TEM(M)
      RADINS=RADTO
      EINS=ETO
  502 TEMCI(M)=TEMCEM+RADTO*DLOG(RADCEM/RADCO)/HCNCEM*UI*(TEM(M)-TEMCEM)
      GO TO 510
  509 TEMCI(M)=TEM(M)
  510 IF(INDAN.EQ.3) GO TO 508
      IF(INDAN.EQ.0) GO TO 503
      IF(INDAN.EQ.2) GO TO 507
      FCI=1.0/(1.0/EINS+RADINS/RADCI*(1.0/ECI-1.0))
      HR=(1.713D-9)*FCI*((TEMINS+460.0)**2+(TEMCI(M)+460.0)**2)*((TEMINS
     1+460.0)+(TEMCI(M)+460.0))
  503 GR=((RADCI-RADINS)**3)*GRV*(DENAN**2)*HECAN*(TEMINS   -TEMCI(M))
     1  /(VISAN**2)
      PR=HSPAN*VISAN/HCNAN
      HCNEQ=HCNAN*0.049*((GR*PR)**0.333)*(PR**0.074)
      HC=HCNEQ/(RADINS*DLOG(RADCI/RADINS))
      IF(INDAN.EQ.0) HR=0.0
      IF(INDINS.EQ.0) GO TO 505
      U(M)=RADTO*(DLOG(RADINS/RADTO)/HCNINS+1.0/(RADINS*(HR+HC))+DLOG(RA
     1DCEM/R ADCO)/HCNCEM)
      GO TO 506
  505 U(M)=1.0/(HR+HC)+RADTO*DLOG(RADCEM/RADCO)/HCNCEM
      GO TO 506
  507 U(M)=RADINS*DLOG(RADCI/RADINS)/HCNAN+RADTO*DLOG(RADCEM/RADCO)
```

```
      1  /HCNCEM
         GO TO 506
  508 U(M)=RADCO*DLOG(RADCEM/RADCO)/HCNCEM
  506 U(M)=1.O/U(M)
         DELU=U(M)-UI
         IF(DABS(DELU).LE.TOLU) GO TO 504
         IF(ITERU.GE.21) GO TO 504
         ITERU=ITERU+1
         UI=U(M)
         GO TO 500
  504 CONTINUE
         HRT(M)=2.O*3.1416*U(M)*(TEM(M)-TEMCEM)/3600.O*RADTO
         RETURN
50401 HRT(M)=MRT1(M)*((1.DO-QX(M))*91.DO*PRS(M)**(.2574DO)
     &+QX(M)*1119.DO*PRS(M)**O.O1267DO)
         NZ=NSAVE
         RETURN
         END
         SUBROUTINE CONDUC                                              CONDUC
         IMPLICIT REAL*8(A-H,O-Z)
         INTEGER WIDTH,HWIDTH
         REAL*8 JC,MRT,MRT1(100)
         REAL*8 LOW( 70, 70)
         DIMENSION A( 70, 70),B(11),D(10,11),E(10,11),F(10,11),H(11),R( 80)
        1,S(10,11),UP( 70,70),G( 80)
         COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
        1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
        2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
         COMMON /CONDU/ A1,DELTIM,DFNF,HCNF,RR,TEMA,TEMR,TIM,NTIM,NTIMI
         COMMON /ENERG/ QX(11),MRT1,NZZ
         NTIM=1
         NN=NR*NZ
         DO 600 K=1,NZ
         DO 600 I=1,NR
  600 T(I,K)=A1*(K-1)*DELZ+TEMA
  601 CONTINUE
         DO 602 K=1,NZ
         DO 602 I=1,NR
         B(K)=1.O/(DELZ**2)
         IM3=I*2-3
         D(I,K)=1.O/((RR**(IM3))*((RR-1.O)**2)*(RADCEM**2))
         F(I,K)=D(I,K)
         H(K)=B(K)
         S(I,K)=-1.O/(DFNF*DELTIM)*T(I,K)
         E(I,K)=-1.O*(B(K)+D(I,K)+F(I,K)+H(K))+S(I,K)/T(I,K)
  602 CONTINUE
         DO 6020 K=1,NZ
         DO 6020 I=1,NR
         IF(K.EQ.1) GO TO 603
         IF(K.EQ.NZ) GO TO 604
         GO TO 6021
  603 IF(I.EQ.1) GO TO 6021
         B(K)=O.O
         D(I,K)=O.O
         F(I,K)=O.O
         H(K)=O.O
         E(I,K)=1.O
         S(I,K)=TEMA
```

```
      GO TO 6021
  604 IF(I.EQ.NR) GO TO 6021
      IF(I.EQ.1) GO TO 6021
      B(K)=0.0
      D(I,K)=0.0
      F(I,K)=0.0
      H(K)=0.0
      E(I,K)=1.0
      S(I,K)=TEMR
 6021 IF(I.EQ.1) GO TO 605
      IF(I.EQ.NR) GO TO 606
      GO TO 6020
  605 B(K)=0.0
      D(I,K)=0.0
      IF(K.GE.M) U(K)=UI
      E(I,K)=1.0+RADTO*U(K)*DLOG(RR)/HCNF
      F(I,K)=-1.0
      H(K)=0.0
      IF(K.GT.M) TEM(K)=TEM(M)
      S(I,K)=RADTO*U(K)*DLOG(RR)/HCNF*TEM(K)
      GO TO 6020
  606 B(K)=0.0
      D(I,K)=0.0
      E(I,K)=1.0
      F(I,K)=0.0
      H(K)=0.0
      IF(INDFLO.EQ.2) GO TO 6022
      S(I,K)=A1*(K-1)*DELZ+TEMA
      GO TO 6020
 6022 S(I,K)=-A1*(K-1)*DELZ+TEMA
 6020 CONTINUE
      DO 609 II=1,NN
      DO 609 KK=1,NN
      A(II,KK)=0.0
  609 CONTINUE
  607 DO 608 I=1,NR
      DO 608 K=1,NZ
      II=I+NR*(K-1)
      IIM1=II-1
      IIMR=II-NR
      IIP1=II+1
      IIPR=II+NR
      A(II,II)=E(I,K)
      IF(IIMR.LE.0) GO TO 6070
      A(II,IIMR)=B(K)
 6070 IF(IIM1.LE.0) GO TO 6071
      A(II,IIM1)=D(I,K)
 6071 IF(IIPR.GT.NN) GO TO 6072
      A(II,IIPR)=H(K)
 6072 IF(IIP1.GT.NN) GO TO 608
      A(II,IIP1)=F(I,K)
  608 R(II)= S(I,K)
      WIDTH=2*NR+1
      HWIDTH=(WIDTH-1)/2
      DO 614 IR=1,NN
      UP(IR,IR)=1.0
      IRMHW=IR-HWIDTH
      IRPHW=IR+HWIDTH
```

```
      MAXR=MAXO(1,IRMHW)
      MINR=MINO(NN,IRPHW)
      DO 611 IS=MAXR,IR
      SUMS=0.0
      ISM1=IS-1
      IF(ISM1.LE.0) GO TO 6100
      IF(MAXR.GT.ISM1) GO TO 6100
      DO 610 IK=MAXR,ISM1
      SUMS=SUMS+LOW(IR,IK)*UP(IK,IS)
  610 CONTINUE
 6100 CONTINUE
  611 LOW(IR,IS)=A(IR,IS)-SUMS
      IRP1=IR+1
      IF(IRP1.GT.MINR) GO TO 614
      DO 613 IS=IRP1,MINR
      SUMR=0.0
      IRM1=IR-1
      IF(IRM1.LE.0) GO TO 6120
      ISMHW=IS-HWIDTH
      MAXS=MAXO(1,ISMHW)
      IF(MAXS.GT.IRM1) GO TO 6120
      DO 612 IK=MAXS,IRM1
      SUMR=SUMR+LOW(IR,IK)*UP(IK,IS)
  612 CONTINUE
 6120 CONTINUE
  613 UP(IR,IS)=(A(IR,IS)-SUMR)/LOW(IR,IR)
  614 CONTINUE
      DO 616 IR=1,NN
      SUMG=0.0
      IRM1=IR-1
      IRMHW=IR-HWIDTH
      MAXR=MAXO(1,IRMHW)
      IF(IRM1.LE.0) GO TO 6150
      DO 615 IK=MAXR,IRM1
      SUMG=SUMG+LOW(IR,IK)*G(IK)
  615 CONTINUE
 6150 CONTINUE
  616 G(IR)=(R(IR)-SUMG)/LOW(IR,IR)
      DO 618 IRB=1,NN
      IR=NN-IRB+1
      SUMR=0.0
      IRP1=IR+1
      IRPHW=IR+HWIDTH
      MINR=MINO(NN,IRPHW)
      IF(IRP1.GT.NN) GO TO 6170
      DO 617 IK=IRP1,MINR
      SUMR=SUMR+UP(IR,IK)*R(IK)
  617 CONTINUE
 6170 CONTINUE
  618 R(IR)=G(IR)-SUMR
      DO 619 I=1,NR
      DO 619 K=1,NZ
      II=I+NR*(K-1)
  619 T(I,K)=R(II)                                          T(I,K)
      IF(NTIM.GE.NTIMI) GO TO 620
      NTIM=NTIM+1
      GO TO 601
  620 TIM=DELTIM*NTIM
```

```
      RETURN
      END
      SUBROUTINE ENERGY                                                 ENERGY
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 JC,MRT,MRT1(100)
      COMMON /ENERG/ QX(11),MRT1,NZZ
      COMMON PRS(12),T(10,11),TEM(11),HRT(11),DENAV(12),U(11),
     1ARA,DIA,DELZ,DPH,GRV,GRVC,JC,MRT,RADTI,RADTO,RADCEM,UINI,ROUGHI,
     2PRSSUR,QXI,UI, INDFLO,  M,NR,NZ
      C1X=1119.0*(PRS(M)**0.01267)-91.0*(PRS(M)**0.2574)
      C1X=C1X*MRT
      C2X=(PRS(M)-PRS(M-1))/DELZ*(1119.0*0.01267*(PRS(M)**(-0.98733))-91
     1.0*0.2574*(PRS(M)**(-0.7426)))
      C2X=C2X*MRT
      C3X=(PRS(M)-PRS(M-1))/DELZ*91.0*0.2574*(PRS(M)**(-0.7426))+
     1(MRT**2)/(DENAV(M)*(ARA**2)*GRVC*JC)*(1.0/DENAV(M)-1.0/DENAV(M-1))
     2/DELZ-1.0/JC
      C3X=C3X*MRT+HRT(M)
      QX(M)=(C1X*QX(M-1)/DELZ-C3X)/(C1X/DELZ+C2X)
      RETURN
      END
```

```
 1          0    1
 2      8  1000.
 3      9  1000.
 4      10  1000.
 5      0   0.
 6      0.302      0.3333333 0.381      0.4166666 0.5        0.000225
 7          0    1   -1
 8      0.0263     0.55       1.4
 9      0.036      0.06642    0.2475     0.000975
10      0.9        0.9        0.96       0.02       2.5
11      2000.0     80.0       108.0      0.800        8750.   1500.
12          5   11      4.0      25     4
13      3.2        1.0        0.01       0.05
14      0.0416667 0.04        0.4
```

APPENDIX D

Key Equations Used for the Production Well Model

$$T' = T + 460$$

$$\Delta X = L/N$$

$$A_x = 3.1416\, d^2/576$$

$$P = P_1 - \Delta P_{old}/2$$

$$G_{gd} = 0.25 + 0.02(API) + (10^{-6})(0.6874 - 3.586API)R_s$$

$$R_p = q'_g/q'_c$$

$$G_{gf} = (R_pG - R_sG_{gd})/(R_p - R_s)$$

$$M_{gf} = 28.966\, G_{gf}$$

$$G_o = 141.5/(131.5 + API)$$

$$\rho_o = (62.4\, G_o + 0.0136\, G_{gd}R_s)/B_c$$

$$f_o = q'_oB_o/(q'_oB_o + q'_wB_w)$$

$$f_w = 1-f_o$$

$$\rho_w = 62.4/B_w$$

$$\rho_L = \rho_of_o + \rho_wf_w$$

$$T_R = T'/T^*_c$$

$$P_R = P/P^*_c$$

$$\rho_{gf} = 2.7PG_{gf}/ZT'$$

$$B_g = 0.0764G_{gf}/\rho_{gf}$$

$$\mu_L = \mu_of_o + \mu_wf_w$$

$$B = 3.5 + (986/T) + 0.01M_{gf}$$

$$C = 2.4-0.2B$$

$$\rho'_{gf} = \rho_{gf}/62.4$$

$$A = \frac{(9.4 + 0.02M_{gf})(T')^{3/2}}{(209 + 19M_{gf} + T')(10^4)}$$

$$\mu_{gf} = A \exp[B(\rho'_{gf})^c]$$

$$\sigma_o = (42.4-0.047T - 0.267API) \times \exp(-0.0007P)$$

$$\sigma_w = (280)52.5-006P$$

$$\sigma_w(74) = 76 \exp(-0.00025P)$$

$$\sigma_w = \left[\frac{(280-T)}{206}[\sigma_w(74)-\sigma_w(280)] + \sigma_w(280)\right]$$

$$\sigma_L = \sigma_o f_o + \sigma_w f_w$$

$$q_w = 6.498(10^{-5})B_w q'_w$$

$$q_o = 6.498(10^{-5})B_o q'_o$$

$$q_L = q_o + q_w$$

$$q_g = 1.157(10^{-5})B_g q'_g$$

$$V_{SL} = q_l/A_x$$

$$V_{sg} = q_g/A_x$$

$$V_m = V_{SL}+V_{sg}$$

$$\lambda_L = V_{SL}/V_m$$

$$N_{FR} = 0.373\ V_m^2/d$$

$$L_1 = 316\ \lambda_L^d 0.302$$

$$L_2 = 0.0009252\ \lambda_L^{-2.4684}$$

$$L_3 = 0.1\ \lambda_L^{-1.4516}$$

$$L_4 = 0.5\ \lambda_L^{-6.738}$$

α = 1 if $\lambda_L > 0.99999$

2 if $10^{-5} > \lambda_L$

3 if $\lambda_L < 0.4$ & $N_{FR} \geq L_1$

or if $\lambda_L \geq 0.4$ & $N_{FR} > L_4$

4 if $0.01 \leq \lambda_L < 0.4$ & $L_3 < N_{FR} \leq L_1$

or if $\lambda_L \geq 0.4$ & $L_3 < N_{FR} \leq L_4$

5 if $\lambda_L < 0.01$ & $N_{FR} < L_1$

or if $\lambda_L \geq 0.01$ & $< N_{FR} < L_2$

6 if $\lambda_L \geq 0.01$ & $L_2 \leq N_{FR} \leq L_3$

$$H_L(O) = a\lambda_L^{b} N_{FR}^{-c}$$

a	b	c
1.065	0.5824	0.0609
0.845	0.5351	0.0173
0.98	0.4846	0.0868

but $H_L(O) \geq \lambda_I$

$$N_{LV} = 1.94\ V_{SL} \left(\rho_L/\sigma_L\right)^{1/4}$$

$$C = (1-\lambda L)\ \ln\ (d'\ \lambda L^{e}\ N_{LV}^{f}\ N_{FR}^{gl})$$

d'	e	f	g'
1	0	0	0
2.96	0.305	-0.4473	0.0978

0.011	-3.768	3.539	-1.614
4.70	-0.3692	0.1244	-0.5056

but $C \geq 0$

$$\Psi = 1 + C[\sin(1.8\phi) - 1/3 \sin^3(1.8\phi)]$$

but $\Psi \geq 0$

$$H_L = H_L(0)\Psi$$

$$0.918\ H_L(0)\Psi$$

$$0.541\ H_L(0)\Psi$$

$$A = (L_3 - N_{FR}) / (L_3 - L_2)$$

$$B = 1 - A$$

$$H_{L,TRAN} = AH_{L,SEGR} + BH_{L,INTR}$$

$$H_g = 1 - H_L$$

$$\sum H_L = 940.4 \sum H_L A_x \Delta_x$$

$$\lambda_g = 1 - \lambda_L$$

$$\rho_n = \rho L \lambda L + \rho_{gf} \lambda_g$$

$$\mu_n = \mu L \lambda L + \mu_{gf} \lambda_g$$

$$Re_n = 124 \rho_n V_m d / \mu_n$$

$$f_n = \left\{ 2\log_{10}[Re_n / (4.5223\log_{10} Re_n - 3.8215)] \right\}^{-2}$$

$$\gamma = \ln (\lambda_L / H_L^2)$$

$$S = \ln(2.2e^{\gamma} - 1.2), \text{ if } 1 < e^{\gamma} < 1.2$$

$\gamma/(0.01853\ \gamma^4 - 0.8725\ \gamma^2 + 3.182\ \gamma - 0.0523)$,

otherwise $f_m = f_n e^s$

$(dp/dx)_f = 0.1863$

$f_m \rho_m V_m^2/d$

$\rho_s = \rho L H_L + \rho_{gf} H_g$

$E_k = \rho s\ V_m\ V_{sg}/4,636.8\ P$

$(dp/dx)_{el} = \rho_s \sin\phi$

$(dp/dx)_{TOT} = 36.667$

$$\left| \frac{(\frac{dp}{dx})_f + (\frac{dp}{dx})_{el}}{1-E_k} \right|$$

$\Delta P_{new} = (dp/dx)_{TOT} \Delta X$

$P_2 = P_1 - \Delta P_{new}$

Nomenclature

A = gas viscosity parameter, cp

a = const

API = API gravity, degrees

A_x = pipe cross-sectional area, ft^2

b = const

B_g= formation volume factor for gas, bbl/scf

B_o= formation volume factor for oil, bbl/STB

B_w= formation volume factor for water, bbl/STB

C = gas viscosity parameter

c = const

d = pipe inside diameter, in

$(dP/dX)_{el}$

$(dP/dX)_f$=friction pressure gradient

$(dP/dX)_{TOT}$ = total pressure gradient

E_k = acceleration parameter

f_m = multiphase friction factor

f_n = no-slip friction factor

f_o = oil cut, frac

f_w = water cut, frac

G = gas gravity (air=1)

g = acceleration due to gravity, ft/sec^2

G_{gd}= dissolved gas gravity (air=1)

G_{gf} = free gas gravity (air=1)

G_o = oil gravity (water=1)

H_g = gas holdup

$H_L(0)$= horizontal liquid holdup

$H_{L,TRAN}$ = transition liquid holdup

L = overall pipe length, miles

L_1 = dimensionless flow number

L_2 = dimensionless flow number

L_3 = dimensionless flow number

L_4 = dimensionless flow number

N = number of pipe increments

N_{FR} = Froude number

N_{LV} = liquid velocity number

P = pressure, psia

P^*_c = corrected pseudocritical pressure, psia

P_1 = inlet pressure, psia

P_2 = incremental outlet pressure, psia

P_R = pseudoreduced pressure, dimensionless

q'_g = inlet gas flow rate, scf/D

q_g = in-line gas flow rate, scf/D

q_L = in-line liquid flow rate, ft^3/sec

q_o = in-line oil flow rate, ft^3/sec

q'_o = inlet oil flow rate, STB/D

q'_w = inlet water flow rate, STB/D

q_w = in-line water flow rate, ft^3/sec

Re_n = no-slip Reynolds number

R_p = produced gas-oil ratio, scf/STB

R_s = solution gas oil ratio, scf/STB

S = multiphase friction parameter

T = fluid temperature, F

T'= absolute fluid temperature, R

T^*_c = corrected pseudocritical temperature

T_R = pseudoreduced temperature

V_m = fluid mixture velocity, ft/sec

V_{sg} = superficial gas velocity, ft/sec

V_{SL} = superficial liquid velocity, ft/sec

Z = gas Z-factor

α = parameter

ΔP = pressure drop, psi

ΔX = calculation increment length, miles

ϕ = pipe inclination angle, degrees

λ_g = no-slip gas holdup

λ_L = no-slip liquid holdup

μ = viscosity, cp

μ_c = oil viscosity, cp

μ_{gf} = free gas viscosity, cp

μ_L = liquid viscosity, cp

μ_n = no-slip fluid viscosity, cp

μ_w = water viscosity, cp

ρ_{gf} = free gas density, gm/cm^3

ρ_L = liquid density, lb/ft^3

ρ_n = no-slip fluid density, lb/ft^3

ρ_o = oil density, lb/ft^3

ρ_s = slip fluid density, lb/ft^3

ρ_w = water density, lb/ft^3

σ_L = gas-liquid interfacial tension, dynes/cm

σ_o = gas-oil interfacial tension, dynes/cm

σ_w = gas-water interfacial tension, dynes/cm

Ψ = liquid holdup correction

APPENDIX E

Listing of the Production Well Program

```
      C CALCULATION OF PRESSURE DROP IN A HORIZONTAL WELL FOR THREE-PHASE FLOW
      C S.M. FAROUQ ALI * DECEMBER 10, 1988
      C NX= NUMBER OF HORIZONTAL SECTIONS
      C DELX(I)= LENGTH OF EACH SECTION, FT
      C DIA(I)= DIAMETER OF EACH SECTION, INCH
      C PHI(I)= INCLINATION OF EACH SECTION WITH HORIZONTAL, UPHILL POSITIVE, DEG
      C TEMP(I)= TEMPERATURE OF EACH SECTION, F
      C RATEO(I)=OIL INFLUX RATE FOR SECTION, STB/D
      C RATEW(I)=WATER INFLUX RATE FOR SECTION, STB/D
      C RATEG(I)=GAS INFLUX RATE FOR SECTION, SCF/D
      C GRAVO= OIL API GRAVITY, DEG
      C GRAVG= GAS DENSITY, DRY (AIR=1)
      C AA, BB= CONSTS IN OIL VIS EQN: VISO=AA*EXP(BB/(T+460)), VISO IN CP, T IN F
      C
      C PEND= PRESSURE AT THE FAR END OF PIPE= PRESS(1) PSIA AT NODE 1
            IMPLICIT REAL*8(A-H,O-$)
            DIMENSION PRESS(101),PRS(100),DELX(100),DIA(100),PHI(100),
           &DELP(100),RATEO(100),RATEW(100),RATEG(100),TEMP(100),
           &AREA(100)
            DATA NX/1/
            DATA DELX/100*5280./
            DATA DIA/100*12./
            DATA PHI/100*30./
            DATA TEMP/100*100./
            DATA RATEO/100*5500./
            DATA RATEW/100*0./
            DATA RATEG/100*250.D6/
            DATA GRAVO,GRAVG,PEND/40.,0.65,1000./
            DATA AA,BB/5.155D0,0.000000/
            ND=NX+1
            DO 68 K=1,NX
      68    AREA(K)=3.1416D0*DIA(K)*DIA(K)/576.D0
            AREA(ND)=AREA(NX)
            SUMO=0.D0
            SUMW=0.D0
            SUMG=0.D0
            SUMHL=0.D0
            PRESS(1)=PEND
            I=1
            DELP(1)=1.D0
      C >>>>>>>>>>>>>>>>ENTRY FOR NEXT SECTION<<<<<<<<<<<<<<<<<
      70    ITER=0
            I=I+1
            J=I-1
            PRINT*,'****** DOING SECTION NO. ',J,' ******'
            SUMO=SUMO+RATEO(J)
            SUMW=SUMW+RATEW(J)
            SUMG=SUMG+RATEG(J)
            DELP(J)=1.D0
      C >>>>>>>>>>>>>>>>ENTRY FOR NEXT ITERATION<<<<<<<<<<<<<<<<<<<<<<<<<
      50    PRESS(I)=PRESS(I-1)-DELP(J)
            ITER=ITER+1
            PRINT*,'                              ITERATION NO. ',ITER
            PRS(J)=(PRESS(I)+PRESS(I-1))/2.D0
            PRSJ=PRS(J)
            TJ=TEMP(J)
            AJ=AREA(J)
            PHIJ=PHI(J)/57.296D0
```

```
      DJ=DIA(J)
      DXJ=DELX(J)
      RS=20.DO
      GGD=0.25DO+0.02DO*GRAVD+(0.6874DO-3.586*GRAVD)*(1.D-6)*RS
      IF(SUMO.LT.1.D-10)SUMO=1.D-10
      RP=SUMG/SUMO
      GGF=(RP*GRAVG-RS*GGD)/(RP-RS)
      IF(GGF.LT.0.DO)GGF=0.DO
      XMGF=28.966DO*GGF
      GO=141.5DO/(131.5DO+GRAVO)
      BO=1.DO
      RHOO=(62.4DO*GO+0.0136*GGD*RS)/BO
      BW=1.DO
      FO=SUMO*BO/(SUMO*BO+SUMW*BW)
      FW=1.DO-FO
      RHOW=62.4/BW
      RHOL=RHOO*FO+RHOW*FW
      TC$=400.DO
      PC$=700.DO
      TABS=TJ+460.DO
      TR=TABS/TC$
      PR=PRSJ/PC$
      ZF=1.DO-3.52DO*PR/(10.DO**(0.9813DO*TR))+0.274DO*PR*PR/(10.DO
     &**(0.8157DO*TR))
      PRINT*,'WE ARE JUST AFTER ZF STMNT,ZF= ',ZF
      RHOGF=2.7DO*PRSJ*GGF/(ZF*TABS)
      BG=0.0764DO*GGF/RHOGF
      VISO=AA*DEXP(BB/TABS)
      VISW=(1776.DO-TJ)/(25.6DO*TJ-89.DO)
      VISL=VISO*FO+VISW*FW
      B=3.5DO+986.DO/TABS+0.01DO*XMGF
      C=2.4DO-0.2DO*B
      RHOGFP=RHOGF/62.4DO
      A=((9.4DO+0.02DO*XMGF)*(TABS**1.5DO))/((209.DO+19.DO*XMGF+
     &TABS)*1.D4)
      VISGF=A*DEXP(B*(RHOGFP**C))
      SIG28O=52.5DO-0.006DO*PRSJ
      SIGO=(42.4DO-0.047DO*TJ-0.267DO*GRAVO)*DEXP(-0.0007DO*PRSJ)
      SIG74=76.DO*DEXP(-0.00025DO*PRSJ)
      SIGW=(SIG74-SIG28O)*(28O.DO-TJ)/(206.DO)+SIG28O
      SIGL=SIGO*FO+SIGW*FW
      PRINT*,'SIGW,SIGL  ',SIGW,SIGL
      QW=(6.498D-5)*BW*SUMW
      QO=(6.498D-5)*BO*SUMO
      QL=QW+QO
      QG=(1.157D-5)*BG*SUMG
      VSL=QL/AJ
      VSG=QG/AJ
      VM=VSL+VSG
      AL=VSL/VM
      PRINT*,'AL=  ',AL
      FRN=0.373DO*VM*VM/DJ
      XL1=316.DO*AL**0.302DO
      XL2=0.0009252DO*AL**(-2.4684DO)
      XL3=0.1DO*AL**(-1.4516DO)
      XL4=0.5DO*AL**(-6.738DO)
      NPASS=2
      MPASS=2
```

```
      IF(AL.GT.0.99999D0)LFA=1
      IF(AL.LT.1.D-5)LFA=2
      IF((AL.LT.0.4D0).AND.(FRN.GE.XL1))LFA=3
      IF((AL.GE.0.4D0).AND.(FRN.GT.XL4))LFA=3
      IF((AL.GE.0.01D0).AND.(AL.LT.0.4D0))NPASS=1
      IF((FRN.GT.XL3).AND.(FRN.LE.XL1))MPASS=1
      IF((NPASS.EQ.1).AND.(MPASS.EQ.1))LFA=4
      NPASS=2
      MPASS=2
      IF((FRN.GT.XL3).AND.(FRN.LE.XL4))NPASS=1
      IF((NPASS.EQ.1).AND.(AL.GE.0.04D0))LFA=4
      IF((AL.LT.0.01D0).AND.(FRN.LT.XL1))LFA=5
      IF((AL.GE.0.01D0).AND.(FRN.LT.XL2))LFA=5
      NPASS=2
      IF((FRN.GE.XL2).AND.(FRN.LE.XL3))NPASS=1
      IF((NPASS.EQ.1).AND.(AL.GE.0.01D0))LFA=6
      IF(LFA.EQ.3)HL0=1.065D0*(AL**0.5824D0)*(FRN**(-0.0609D0))
      IF(LFA.EQ.4)HL0=0.845D0*(AL**0.5351D0)*(FRN**(-0.0173))
      IF(LFA.EQ.4)HL0IN=HL0
      IF(LFA.EQ.5)HL0=0.980D0*(AL**0.4846D0)*(FRN**(-0.0868D0))
      IF(LFA.EQ.5)HL0SG=HL0
      IF(HL0.LT.AL)HL0=AL
      XNLV=1.94D0*VSL*(RHOL/SIGL)**0.25D0
      IF((LFA.EQ.3).AND.(PHIJ.LT.1.57D0))CC=0.D0
      IF((LFA.EQ.4).AND.(PHIJ.LT.1.57D0))CC=(1.D0-AL)*DLOG(2.96D0*
     &(AL**0.305D0)*XNLV**(-0.4473D0)*(FRN**0.0978D0))
      IF((LFA.EQ.5).AND.(PHIJ.LT.1.57D0))CC=(1.D0-AL)*DLOG(.011D0*
     &(AL**(-3.768D0))*XNLV**(3.539D0)*(FRN**(-1.614D0)))
      IF(PHIJ.GE.1.57D0)CC=(1.D0-AL)*DLOG(4.7D0*
     &(AL**(-0.3692D0))*XNLV**(0.12440D0)*(FRN**(-.5056D0)))
      IF(CC.LT.0.D0)CC=0.D0
      PSI=1.D0+CC*(DSIN(1.8D0*PHIJ)-(DSIN(1.8D0*PHIJ))**3/3.D0)
      PRINT*,'LIQ HOLDUP CC=  ',CC,'  LFA=',LFA,'  PSI=',PSI
      IF(PSI.LT.0.D0)PSI=0.D0
      HL=HL0*PSI
      PRINT*,'AFTER LINE 117,HL,HL0 ',HL,HL0
      IF(PHIJ.LT.1.57D0)HL=HL*0.918D0
      IF(PHIJ.GE.1.57D0)HL=HL*0.541D0
      AQ=(XL3-FRN)/(XL3-XL2)
      BQ=1.D0-AQ
      IF(LFA.EQ.6)HL=AQ*HL0SG+BQ*HL0IN
      HG=1.D0-HL
      GL=1.D0-AL
      RHON=RHOL*AL+RHOGF*GL
      VISN=VISL*AL+VISGF*GL
      REN=124.D0*RHON*VM*DJ/VISN
      FN=1.D0/(2.D0*DLOG10(REN/(4.5223D0*DLOG10(REN)-3.8215D0)))**2
      Y=DLOG(AL/(HL*HL))
      IF((DEXP(Y).GT.1.D0).AND.(DEXP(Y).LT.1.2D0))GO TO 30
      S=Y/(0.01853D0*Y**4-0.8725D0*Y*Y+3.182D0*Y-0.0523D0)
      GO TO 40
30    S=DLOG(2.2D0*DEXP(Y)-1.2D0)
40    FM=FN*DEXP(S)
      DPDXF=0.1863D0*FM*RHON*VM*VM/DJ
      RHOS=RHOL*HL+RHOGF*HG
      EK=RHOS*VM*VSG/(4636.8D0*PRSJ)
      DPDXE=RHOS*DSIN(PHIJ)
      DPDXT=(DPDXF+DPDXE)/(1.D0-EK)
```

```
      DELPN=(DPDXT*DXJ)/5280.D0
      IF(DABS(DELPN-DELP(J)).LT.0.1D0)GO TO 100
      DELP(J)=DELPN
      GO TO 50
100   SUMHL=SUMHL+940.4D0*HL*AJ*DXJ/5280.D0
      IF(I.EQ.ND)GO TO 110
      GO TO 70
110   PRINT*,'PRESSURE DROP',(DELP(J),J=1,NX)
      PRINT*,'SUMHL,VM ',SUMHL,VM,'     ALFA=',LFA
      STOP
      END
```